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Publication date:
2014

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Citation (APA):
Göçmen Bozkurt, T., Giebel, G., Poulsen, N. K., & Mirzaei, M. (2014). *Wind Speed Estimation and Parameterization of Wake Models for Downregulated Offshore Wind Farms*. Poster session presented at European Wind Energy Conference & Exhibition 2014, Barcelona, Spain. http://www.ewea.org/annual2014/conference/

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PO. ID 131

Wind Speed Estimation and Parameterization of Wake Models for Downregulated Offshore Wind Farms

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Abstract

The estimation of possible (or available) power of a downregulated offshore wind farm is the content of the **PossPOW project** (See PossPOW Poster ID: 149). The main challenges of this estimation process are:

1) to **determine the free stream equivalent wind speed** at the turbine level since the accuracy of nacelle anemometers are in question and power curve derivation is no longer applicable during downregulation
2) to apply **a real-time wake model** which can calculate the power production as if the wind farm was operating normally even in short downregulation periods. However, most existing wake models have only been used to acquire long term, statistical information and verified using 10-min averaged data

The proposed methodologies to overcome those challenges are presented in this poster.

Wind Speed Estimation

Using the general power expression; $\mathbf{P = \frac{1}{2}\rho\, C_P(\lambda,\theta)\, \pi R^2 U^3}$

Active Power $P_{measured}$ →
Rotational Speed $\omega_{measured}$ →
Pitch Angle $\theta_{measured}$ →

Aerodynamic backward calculation of wind speed → Incoming Wind Speed U_{inflow}

↑ *Temperature & Pressure*

The power coefficient approximation of Heier[1]

$$C_P(\lambda,\theta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\theta - c_4\theta^{c_5} - c_6\right)\exp\left(\frac{-c_7}{\lambda_i}\right)$$

$$\lambda_i = \left[\left(\frac{1}{\lambda + c_8\theta}\right) - \left(\frac{c_9}{\theta^3+1}\right)\right]^{-1}$$

The coefficients in the expression, c_1 to c_9, strongly depend on the blade shape, in other words, the turbine type. They have been adjusted according to the turbines in the case studies, partially using the research of Raiambal et.al.[2] and partially the dataset itself.

The wind speed was calculated for each turbine iteratively using **Horns Rev-I** offshore wind farm and **NREL 5 MW** single turbine simulations[3]. Both cases have been investigated using **second-wise datasets** extracted during both normal operation and under curtailment.

Horns Rev - *Normal Operation*

The algorithm is tested using the dataset provided by Vattenfall which covers a 35-hours period where the whole operational range is contained i.e. below cut-in to above rated region.

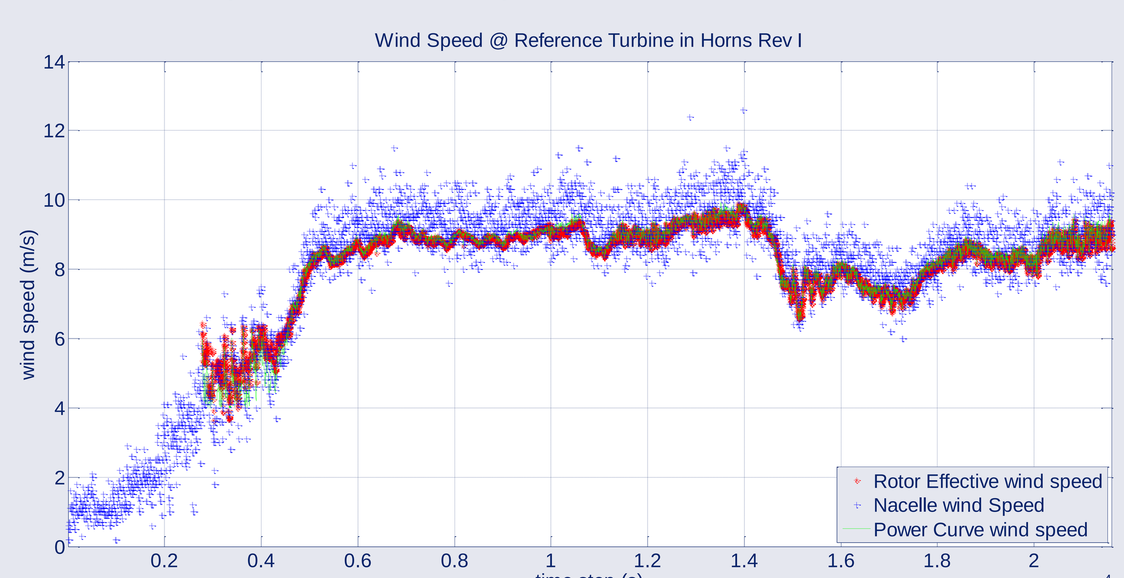

Figure 1 – Wind Speed Comparison at the reference turbine located in Horns Rev Wind Farm, during normal (ideal) operation

Horns Rev *Down-Regulation*

The second dataset from Horns Rev covers approximately 2 hours of data extracted during down-regulation. In Figure 2 (a), the characteristics of the downregulation which in total lasts approximately one hour may be seen.

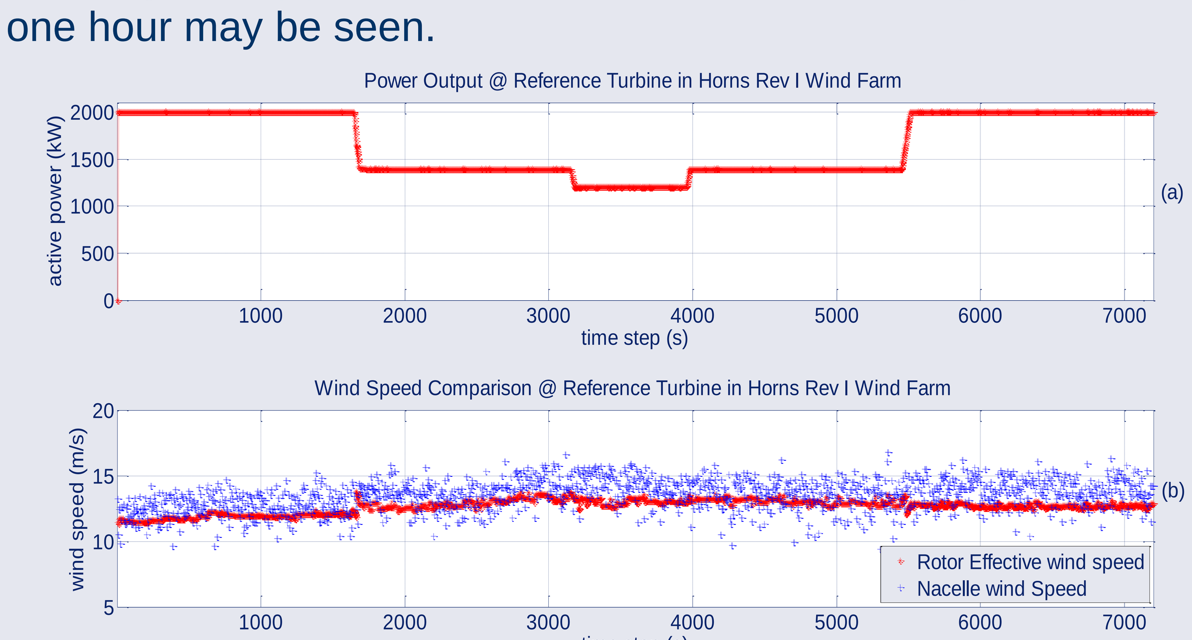

Figure 2 – (a) Power Output (b) - Wind Speed Comparison of the reference turbine located in Horns Rev wind farm during downregulation

NREL 5 MW

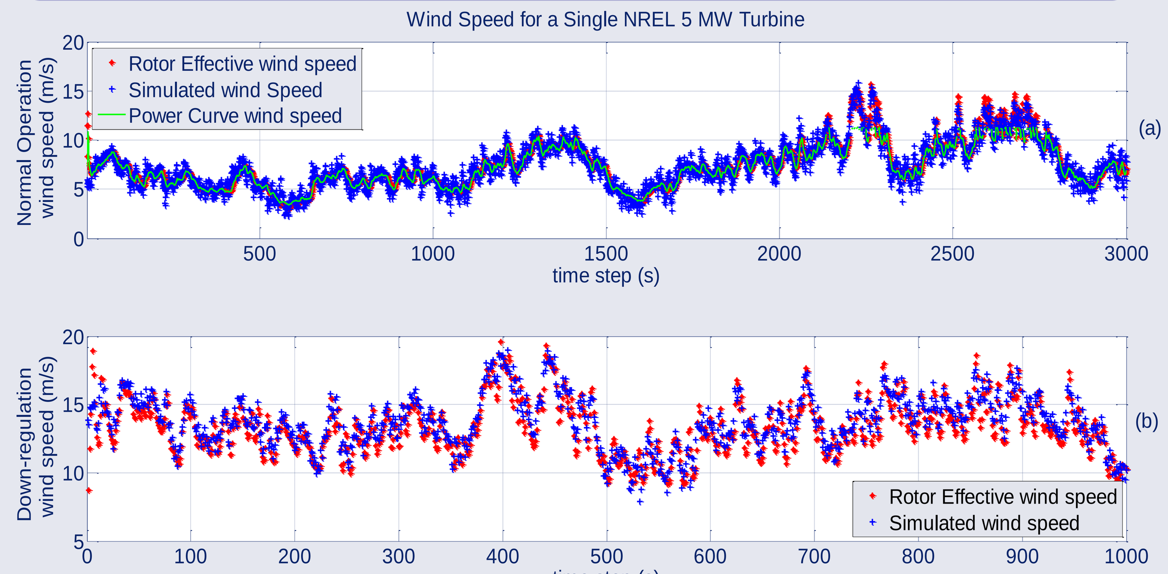

Figure 3 – Wind Speed Comparison of a single NREL 5 MW turbine during (a) normal operation (b) 50% downregulation

It is concluded that, the model is able to reproduce the simulated wind profile hitting the NREL 5 MW turbine for both normally operated and downregulated cases.

Wake Model Recalibration for Real Time

The single wake model proposed by GCLarsen has been used for recalibration due to its robustness and simplicity. The model has been implemented in WindPro and shown to perform well also on offshore[4]. there are 2 parameters to adjust in the single wake case:

$$u_x(x,r) = -\frac{U_\infty}{9}\left(c_T A (x_0+\Delta x)^{-2}\right)^{1/3}\left\{r^{3/2}\left(3c_1^2 c_T A (x_0+\Delta x)\right)^{-1/2} - \left(\frac{35}{2\pi}\right)^{3/10}\left(3c_1^2\right)^{-1/5}\right\}^2$$

The estimated second-wise effective wind speed values of Horns Rev during normal operation were used for calibration and the results have been compared with the downregulated dataset with caution. All data was filtered for easterly winds i.e. 90±10° .

GCLarsen Single Wake Recalibration

The effective wind speeds of the upstream and downstream turbines have been averaged row-by-row to obtain a single incoming and downstream wind speed. The model was fit to the dataset using nonlinear least squares estimates (nonlinear LSE) and the parameters together with the goodness of fit is presented below.

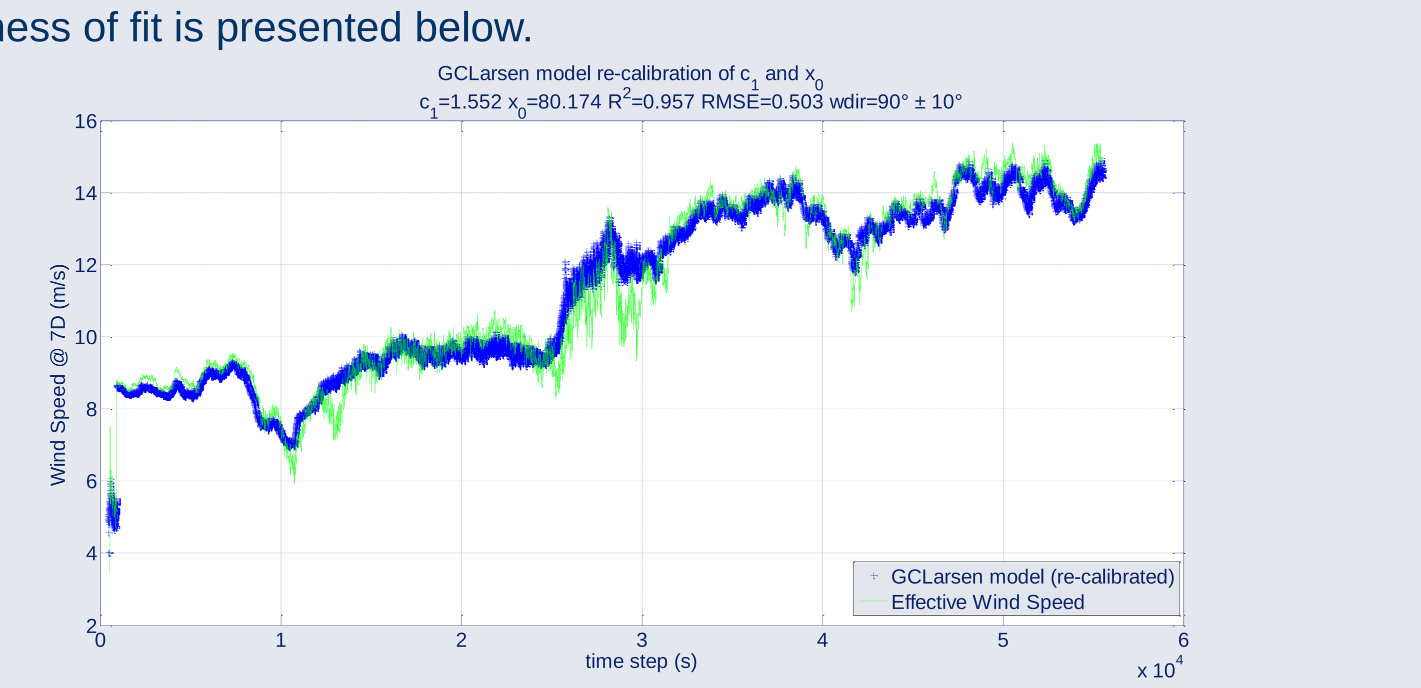

Figure 4 – GCLarsen Single Wake model recalibration using Horns Rev normal operation dataset : $c_1 = 1.552$, $x_0 = 80.174$ Goodness of Fit : $R^2 = 0.957$ and $RMSE = 0.503$

Recalibrated Model Results

The downregulation period was used to test the new model parameters therefore the downstream wind speed estimated by the calibrated GCLarsen is expected to be lower than the observations.

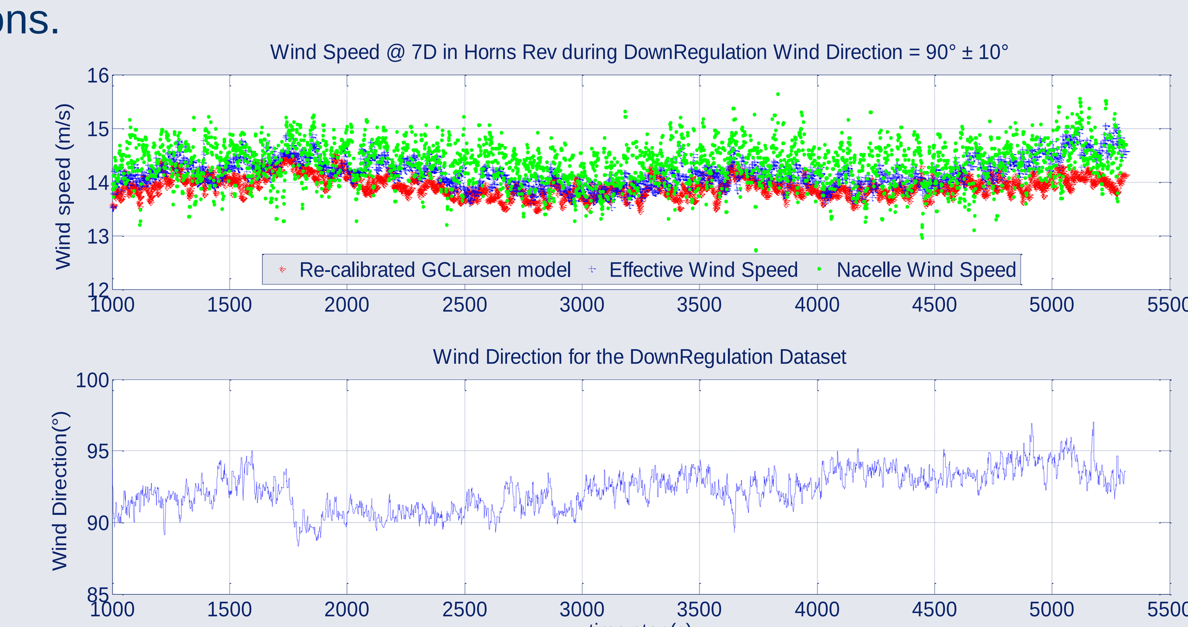

Figure 5 – Comparison of Wind Speed values for filtered wind direction in 90±10° bin @ 7D downstream of a turbine for easterly winds in Horns Rev during downregulation

The modelled wind speed is lower than the observations as expected. However, the difference is not significant probably due to the high wind speeds in the dataset, even in the wake where c_T is rather independent on the pitch angle variations (therefore the downregulation) for high wind speeds[5] .

Conclusions

As work packages of the PossPOW project, an aerodynamic backward calculation of wind speed methodology using active power, pitch angle and rotational speed measurements was proposed. The modelled rotor effective wind speed profile was compared to the nacelle anemometer measurements and the power curve wind speed estimations for Horns Rev case and to the simulated wind flow for NREL 5MW case. Then Horns Rev effective wind speed profiles were used to calibrate GCLarsen single wake model for real time and the calibration was tested using a downregulated dataset.

Future Works

Firstly, the recalibration of the GCLarsen single wake model has to be tested and developed using more representative dataset extracted during normal operation. Then, the recalibrated model has to be further re-parameterized for wind farm scale considering the dynamic factors such as wind direction variability, the wake meandering concept and the 'sweeping' of the wind farm when applying the wake model row by row.

Acknowledgements

The project partners of PossPOW are Vattenfall, Siemens, Vestas, and DONG. PossPOW is financed by Energinet.dk under the Public Service Obligation, ForskEL contract 2012-1-10763. The author would like to thank Mads Rajczyk Skjelmose and Jesper Runge Kristoffersen from Vattenfall for their cooperation and supply of the datasets.

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